Photon-assisted transport in a carbon nanotube

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We investigate the quantum transport through a single-wall carbon nanotube connected to leads in the presence of an external radiation field. We analyze the conductance spectrum as a function of the frequency and strength of the field. We found that above a critical value of the field intensity, an enhancement of the conductance, or suppressed resistance, as a function of the field strength occurs. The conductance increases displaying oscillations which amplitude shows a strong dependence on the field frequency. For low radiation energies in comparison to the lead-CNT coupling energies, the oscillations evolve toward a structure of well defined steps in the conductance. We have shown that in this range of frequencies the field intensity dependence of the conductance can give direct information of single-walled carbon nanotubes energy spectra.

I. INTRODUCTION

The electronic transport through carbon nanotubes (CNT's) has received much attention in the last decade due to the peculiar features of the band structure of these quasi-one dimensional systems[1,2]. Depending of their diameter and chirality CNT's can exhibit metallic or semiconducting behavior and therefore be promising candidates for new carbon nanotube-based electronic devices. Some of them have already been realized, such as field effect transistors[3,4], field emission displays[5] and nanosensors[6].

The quantum-mechanic behavior of the electronic transport in CNT's has been experimentally confirmed by Tans et. al.[7] whom showed that individual single-walled carbon nanotube (SWCNT) between two contacts behaves as coherent quantum wires, and by Frank et. al.[8], they have proved the quantization of the conductance of multiwalled carbon nanotubes. On the other hand, effects of time-dependent potentials on transport properties of CNT's has been studied previously for various authors[9,10,11]. Recently, Kim et. al.[12] studied experimentally the microwave response of individual multiwall CNT finding an enhancement of the linear conductance under the microwave radiation.

In this work, we investigate the quantum transport through SWCNT connected to leads in the presence of an external radiation field. Specifically, we consider a time-dependent spatially uniform potential applied normal to the tube for modeling the effect of the radiation field. This problem is closely related to photon-assisted tunneling in nanostructures[13]. Basically, the external field induces the apparition of side-bands in the spectrum and therefore the tunneling current is drastically modified[14].

We solve the problem using standard nonequilibrium Green's function (NGF) techniques. The conductance is calculated by the Landauer formula in terms of the transmission function which is obtained from the retarded and advanced Green's function of the SWCNT in the presence of the field, and the coupling of the nanotube to the leads[15]. We analyze the conductance spectra as a function of the frequency and amplitude of the external time-varying potential. We found that above a critical value of the radiation field intensity, an enhancement of the conductance as a function of the field strength occurs. The conductance increases displaying oscillations with amplitudes strongly dependent on the field frequency. For low photon energies in comparison to the lead-CNT coupling energies, the oscillations evolve to a structure of well defined steps. This effect can be explained as due to the electric-field induced side-band resonances that increase the LDOS at the Fermi energy opening new channels for electronic transmission.

II. MODEL

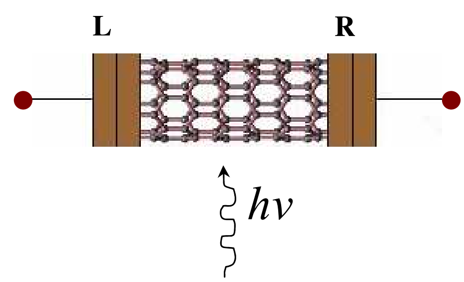

FIG. 1: Schematized view of the CNT system considered.

The system under consideration is formed by a SWCNT embedded between two leads. The full system is modeled by the following Hamiltonian within a noninteracting picture, that can be written as

$$H = H_L + H_{CN} + H_{LCN}, \tag{1}$$

with

$$\begin{aligned} H_L &= \sum_{q,\alpha} \varepsilon_{q_\alpha}(d^\dagger_{q_\alpha} d_{q_\alpha}), \\ H_{CN} &= \sum_k \varepsilon_k(c^\dagger_k c_k), \\ H_{LCN} &= \sum_{n=1,\alpha=l,r}^{N} (V_{q_\alpha,k} d^\dagger_{q\alpha} c_k + V^*_{q_\alpha,k} c^\dagger_k d_{q\alpha}), \end{aligned} \quad (2)$$

where $c^\dagger_k$ is the creation operator of an electron at the state k of the carbon nanotube, and $d^\dagger_{q,\alpha}$ is the corresponding operator of an electron in the state q of the right ($\alpha = R$) or left ($\alpha = L$) lead. Here ε_k denotes the energy spectrum of a metallic carbon nanotube[2].

We will solve the problem using standard non-equilibrium Green's function techniques. In this formalism the retarded and correlated Green's function can be expressed by $G^r_k(t,t') = -i\theta(t-t')\langle\{c_k(t), c^\dagger_k(t')\}\rangle$ and $G^<_k(t,t') = -i\langle c_k(t') c^\dagger_k(t)\rangle$. Where the Green's functions G^r and $G^<$ are obtained from the Dyson equation $G^r = [(g^r)^{-1} - \Sigma^r]$, and the Keldysh equation $G^< = G^r \Sigma^< G^a$. Where g^r is the unperturbed Green's function of the nanotube. The self energies are given by,$\Sigma^r = -i/2(\Gamma_L + \Gamma_R)$ and $\Sigma^< = -i/2(f_L\Gamma_L + f_R\Gamma_R)$ and $f_\alpha(\varepsilon)$ is the Fermi distribution. The line-width functions $\Gamma_\alpha(\varepsilon)$, in the wide bandwidth approximation, are taken to be independent of the energy and energy levels. Once the Green's function G^r and $G^<$ are known, an expression for the current can be derived[16]:

$$I_\alpha = \frac{-2e}{\hbar} \int dt' \int \frac{d\varepsilon}{2\pi} \Im m \left(\sum_k \left\{ e^{-i\varepsilon(t'-t)/\hbar} e^{-i/\hbar \int V(t'')dt''} \Gamma_\alpha(\varepsilon) \left[G^<(t,t') + f_\alpha(\varepsilon) G^r(t,t') \right] \right\} \right), \quad (3)$$

If the CNT is perturbed by a time-dependent, spatially uniform, potential given by: $V(t) = V_0 \cos(\omega t)$,[14] the zero-voltage limit linear conductance will be given by[13]:

$$G = \lim_{V\to 0} \frac{\langle I \rangle}{V} = \frac{2e^2}{\hbar} \int \frac{d\varepsilon}{2\pi} \sum_{nk} J_n^2 \left(\frac{V_0}{\hbar\omega} \right) (-\frac{\partial f(\varepsilon)}{\partial \varepsilon}) \Gamma_L G^r_k(\varepsilon) \Gamma_R G^a_k(\varepsilon), \quad (4)$$

where $\langle I \rangle$ is the time-averaged current. For this simple model an effective density of states can be derived,

$$\tilde{\rho}(\varepsilon) = \sum_n |J_n(\frac{V_0}{\hbar\omega})|^2 \rho_0(\varepsilon - n\hbar\omega) \quad (5)$$

where $\rho_0(\varepsilon)$ is the bare density of states corresponding to the CNT in the absence of the perturbing potential. In the case of a $(n,0)$ CNT in the tight-binding approximation this density of states can be expressed in analytic form as[17]:

$$\rho_0(\varepsilon) = \frac{1}{\pi} \Im m \sum_{j=0}^{2n} \left(\frac{-2/3(\varepsilon + i0^+)}{i\pi\sqrt{16cos^2(\frac{\pi}{n}j) - [(\varepsilon+i0^+)^2 - 1 - 2cos^2(\frac{\pi}{n}j)]^2}} \right)$$

The above equation can be physically interpreted as follow: photon absorption ($n > 0$) and emission ($n < 0$) can be viewed as creating an effective electron density of states at energies $\varepsilon_n = n\hbar\omega$ with a probability given by $|J_n(\frac{V_0}{\hbar\omega})|^2$.

III. RESULTS

In what follow we will adopt the parameters: $\gamma = 2.75eV$, which is the CNT hoping integral, and $\Gamma_L = \Gamma_R = \Gamma = 0.001\gamma$, the leads-CNT coupling parameters. Figure 2 shows the DOS of a zigzag CNT (12,0) as a function of the energy in units of γ, for different values of the

radiation field strength V_0 and for a particular photon energy $h\nu = 0.0005\gamma$ ($\nu = 332.5GHz$). It can be seen that the CNT pseudo-gap is strongly modified by the presence of the sideband resonances appearing due to the presence of the radiation field. These resonances are more dense near the Fermi energy for increasing values of the field strength. This effect has strong influence on the system conductance due to the opening of new channels for electronic transmission, as we will see below.

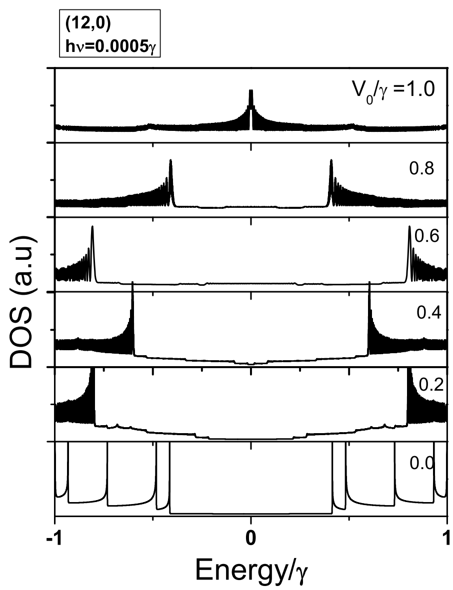

FIG. 2: Density of states for a (12,0)CNT under a radiation field of $h\nu = 0.0005\gamma$ and different values of the field strength.

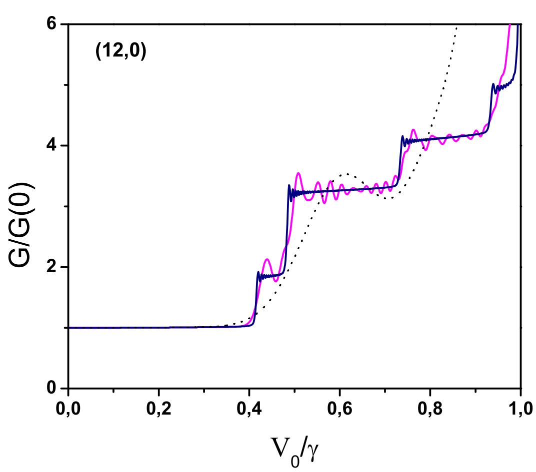

FIG. 3: (color online)Normalized linear conductance of a (12,0) CNT as a function of the oscillating field strength in unit of γ, for $h\nu = 0.0005\gamma$ (solid blue line), $h\nu = 0.005\gamma$ (solid magenta line) and $h\nu = 0.05\gamma$ (dotted line).

In figure 3 we have displayed the linear normalized conductance $G/G(0)$, where $G(0)$ is the conductance for zero field, for the CNT (12,0) as a function of the intensity of the radiation field. We have plotted the corresponding conductance for different photon energies $h\nu = 0.0005\gamma$ (blue online), $h\nu = 0.005\gamma$ (magenta online)and $h\nu = 0.05\gamma$ (dotted line). It can be observed that in all cases the conductance increases as a function of the radiation field strength. For low frequencies, $\nu < \Gamma/h$ the conductance presents a very well defined structure of steps. For increasing frequencies some oscillations appears by inducing a complete suppression of the step features for higher frequencies.

The steps structure in the conductance for low frequencies $\nu < \Gamma/h$, can be understood because of in that range of frequencies the system is found in a quasi-static regime, and the spectrum as a function of the strength of the radiation field V_0, is just linearly shifted. As the field intensity increases the Van Hove singularities cross the Fermi energy leading to an abrupt increase in the conductance. In fact, each step in the conductance reflects the energy position of the corresponding Van Hove singularity of the nanotube DOS. Figure 4 shows the normalized conductance versus the strength of the radiation field for a (15,0) CNT. There we have included the corresponding DOS in the same energy range.

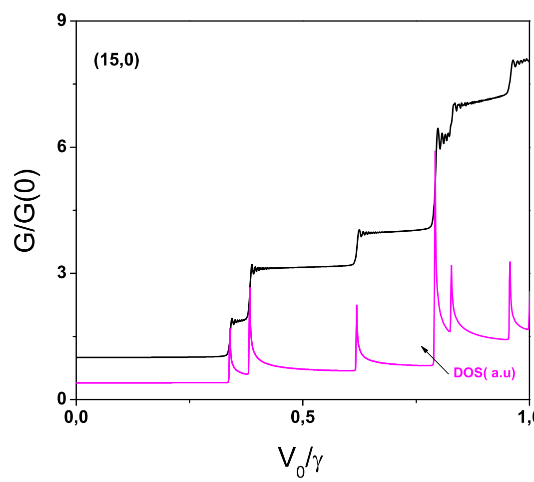

FIG. 4: (color online) Normalized conductance of a (15,0) CNT as a function of the oscillating field strength, in units of γ, for $h\nu = 0.0005\gamma$. It is also plotted the corresponding DOS of the CNT in the same energy range.

In figure 5 we show the behavior of the normalized resistance versus radiation-field strength with the nanotube radius. The figure displays plots for (a) (9,0) and (b) (18,0) metallic nanotubes. In both cases the step

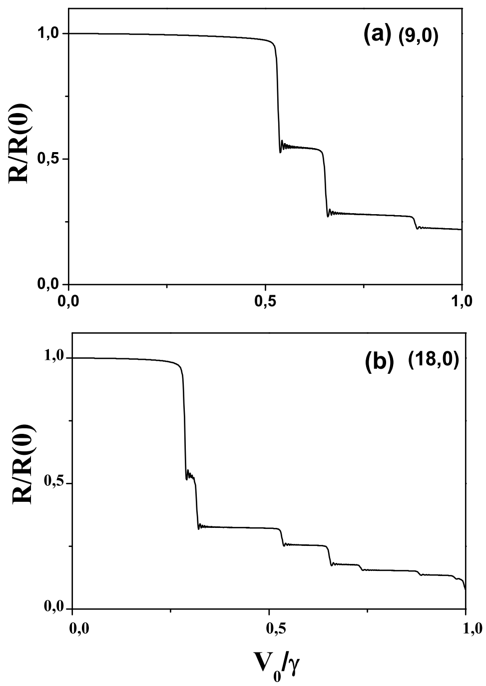

FIG. 5: Normalized resistance for CNTs of different diameters as function of the oscillating field strength, (a) (9,0) CNT and (b) (18,0) CNT, for $h\nu = 0.0005\gamma$.

structure is clearly manifested with increasing number of steps for larger radii. This steps structure is a reflex of the cuasi-one dimensional density of states of the CNT.

The above results can be compared with the experimental results of Kim at al.[12] whom studied the microwave response of an individual CNT. They effectively found that the resistance decreases as a function of the radiation field power regardless of the frequency. In their experiment the step structure is not observed because they studied a multiwall nanotube of about 25nm wide. In this case the cuasi-one dimensional character of the CNT DOS is completely suppressed.

IV. SUMMARY

We have investigated quantum transport through SWCNT connected to leads in the presence of an external radiation field. We studied the conductance spectra as a function of the frequency and of the field strength. We found that above a critical value of the field strength an enhancement of the conductance, or suppressed resistance, as a function of the field intensity occurs. The conductance increases displaying oscillations which amplitude shows a strong dependence on the frequency of the oscillating field. For low radiation energies in comparison to the lead-CNT coupling energies, the oscillations evolve toward a structure of well defined steps in the conductance. We have shown that in this range of frequencies the field intensity dependence of the conductance can give direct information of SWCNT energy spectra.

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